

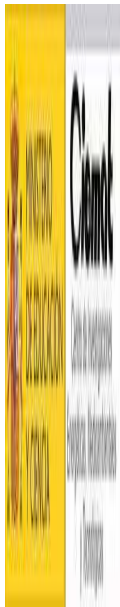


# **DESIGN, CONSTRUCTION AND ASSEMBLY OF THE SPANISH STELLARATOR TJ-II. ENGINEERING EXPERIENCE**

**ENGINEERING & SERVICES**

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CIEMAT**

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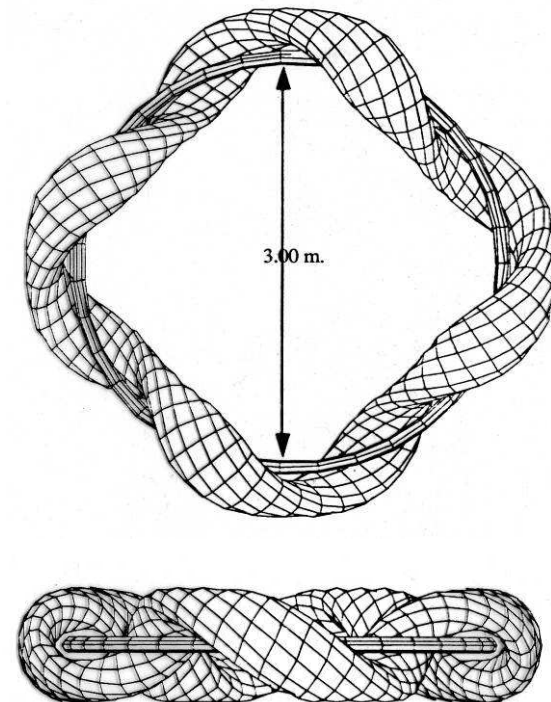
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# Description of the device

## TJ-II characteristics:

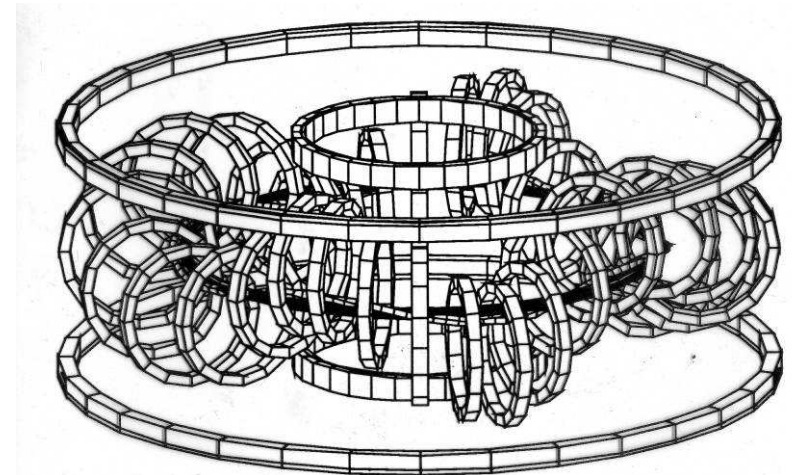
- Medium size stellarator (no plasma current)
- Major radius 1.5 m
- Minor radius 0.2÷0.25 m  
(medium plasma radius)
- Swing radius 0.28 m
- Average magnetic field 1 T
- Number of periods 4



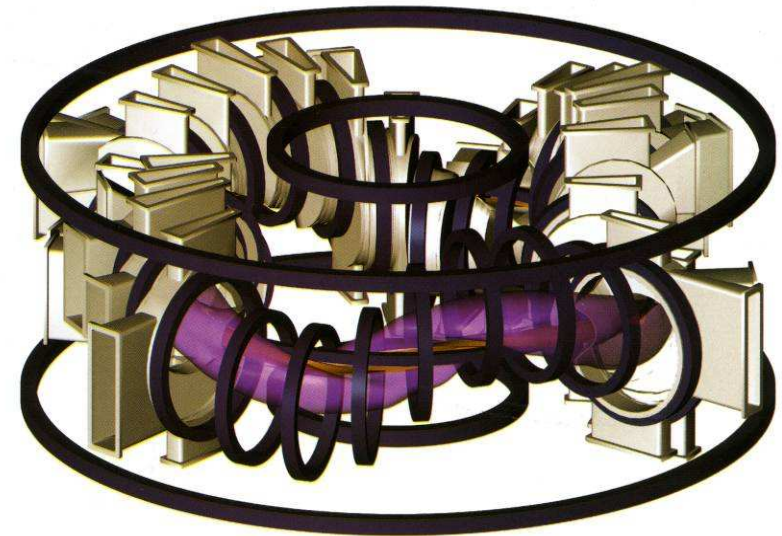
## Description of the device

### The main components of TJ-II are:

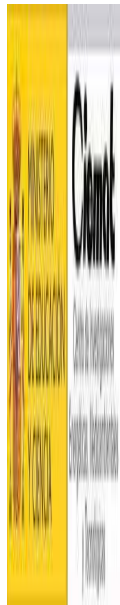
- Central coils (HC)
- Toroidal Field Coils (TF)
- Vacuum vessel (VV)
- Poloidal field coils (PF)
- Support structure (SS)



COIL SYSTEM



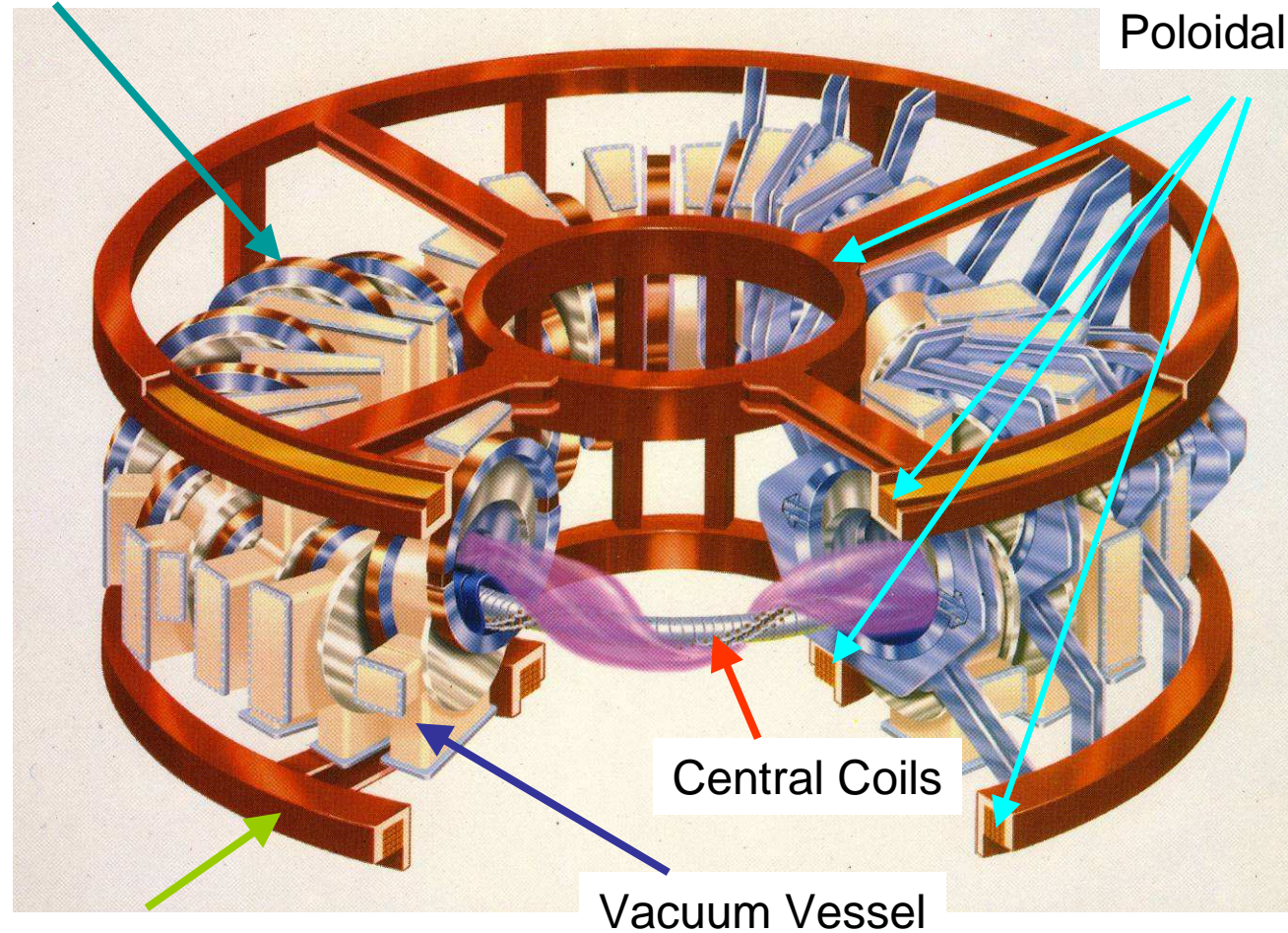




## Description of the device

Toroidal Field Coils

Poloidal Field Coils

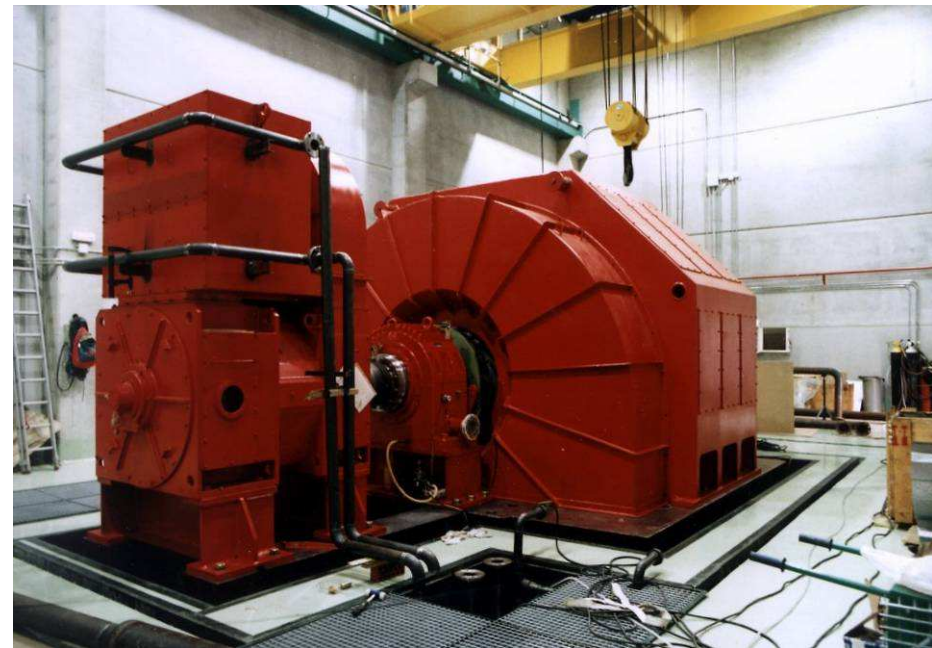


Support structure

## Description of the device

### The main auxiliaries of TJ-II are:

- Power supplies
- Vacuum system
- Cooling system
- Plasma heating systems
  - ECRH
  - NBI
- Control system



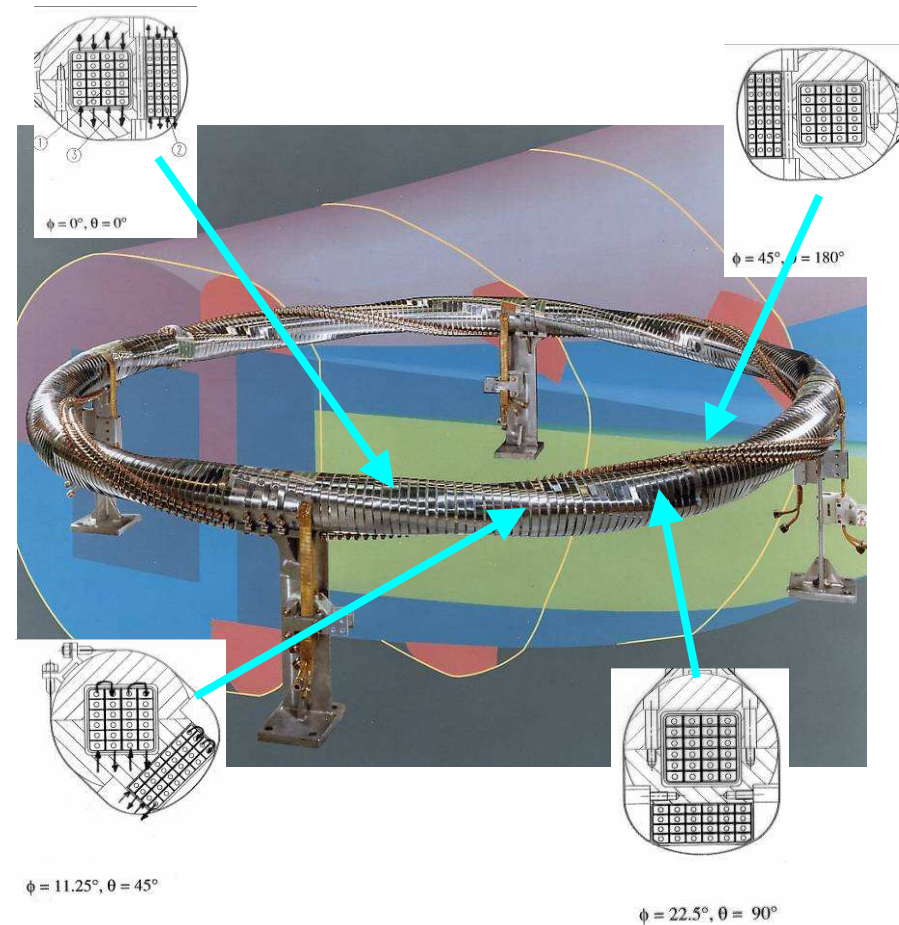


# Description of the device

## Central coils (HC):

- Circular coil (CC): 280 kA-v
  - 1.5 m radius
  - Hollow copper profiles
- Helical coil (HX): 260 kA-v
  - 7 cm swing radius over CC
  - Hollow copper profiles
- 304 LN ss casing structure
  - Two halves, CC inside
  - HX wound around
  - 4 legs attached to SS

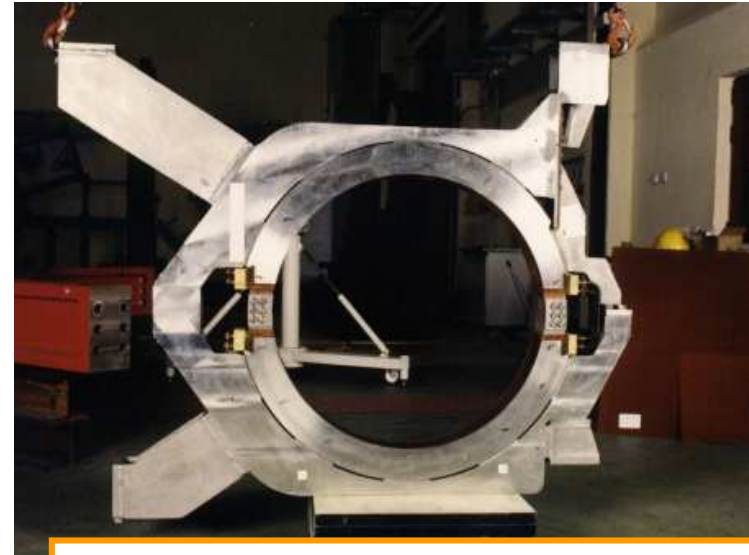
**Manufacturer NOELL(+ABB)**



## Description of the device

### Toroidal Field coils (TF):

- 28 coils: 260 kA-v
  - 0.425 m radius
  - Copper discs + cooling tube
  - 8 turns divided in two halves
- 4 coils: 292.5 kA-v
  - 0.475 radius
  - Copper discs + cooling tube
  - 9 turns in two halves
- 304 LN ss structure
  - Two halves U-shape casing
  - Two halves rings
  - 4 legs attached to SS rings



**Manufacturer TESLA Engin. Lt**

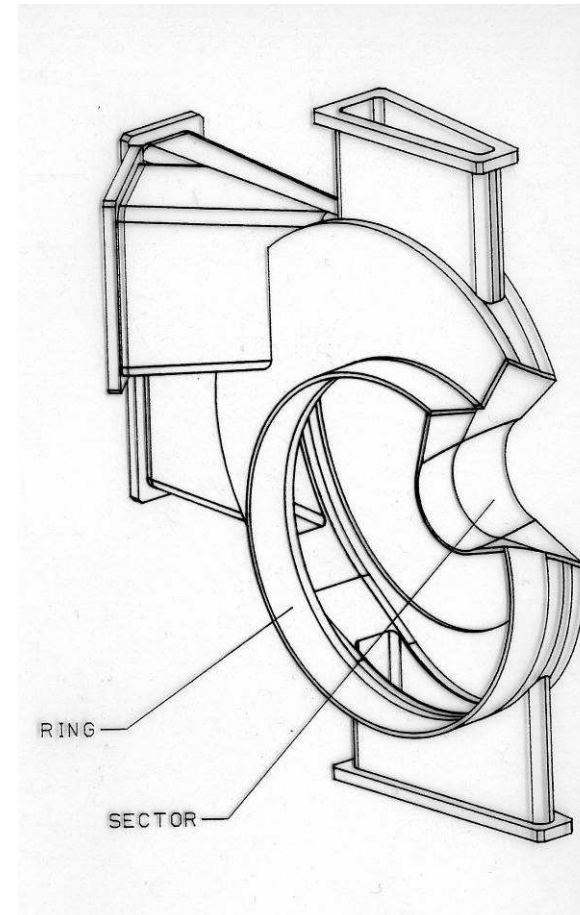


# Description of the device

## Vacuum Vessel (VV):

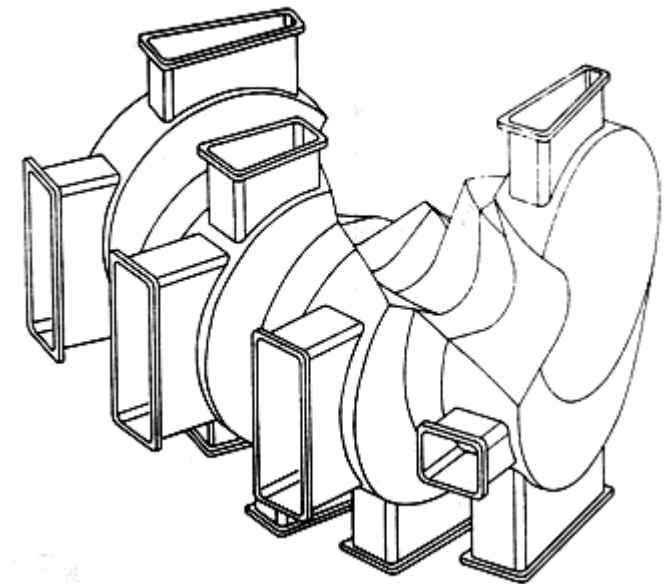
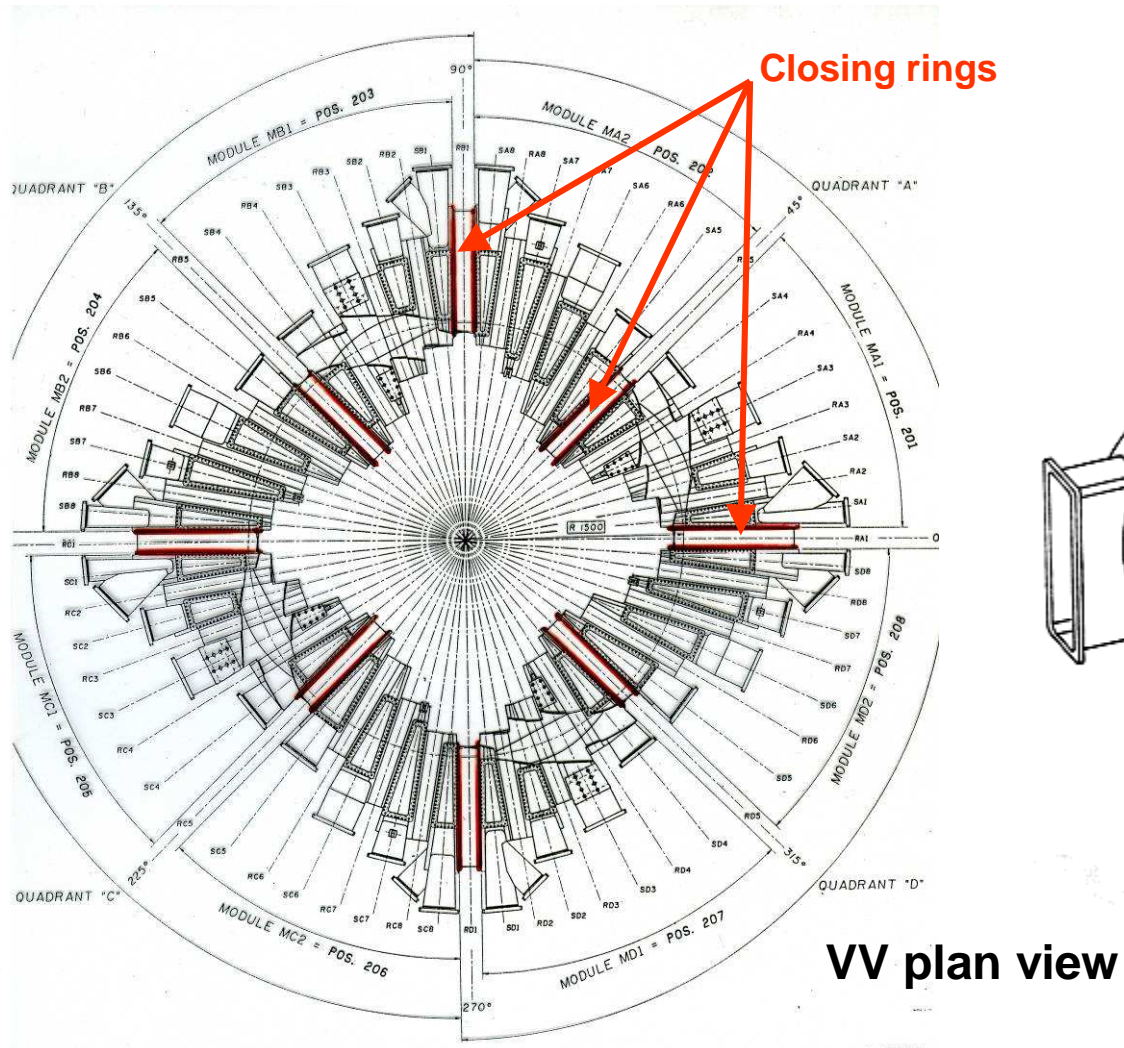
**Manufacturer De Pretto Escher Wyss**

- Material
  - 304 LN  $\mu_{rel} \leq 1.01$
  - Thickness 10 mm
  - Thickness groove 7 mm
  - Flanges 25 mm
- 32 sectors 2, 3 or 4 ports each
- 32 rings for TF coils
- Final part arrangement
  - 8 sectors (octants)
  - 8 closing rings





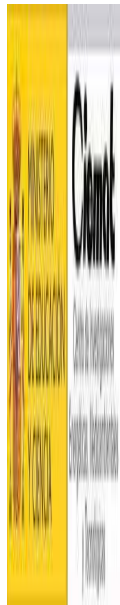
# Description of the device



**VV octant**

**VV plan view**

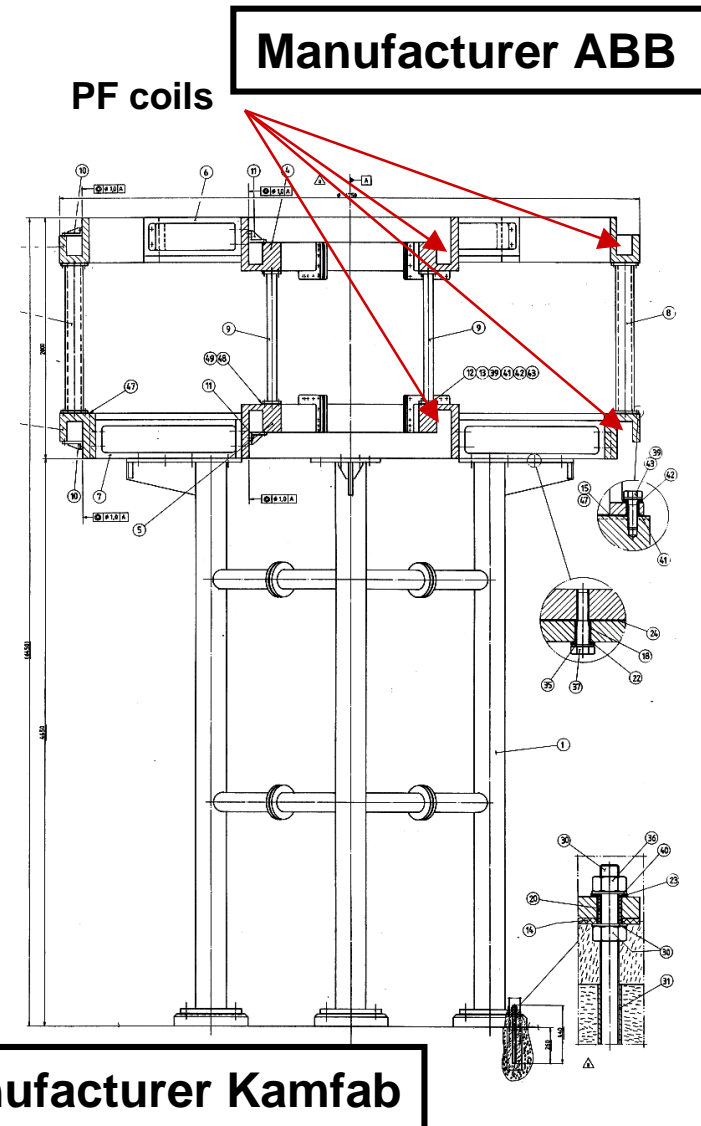




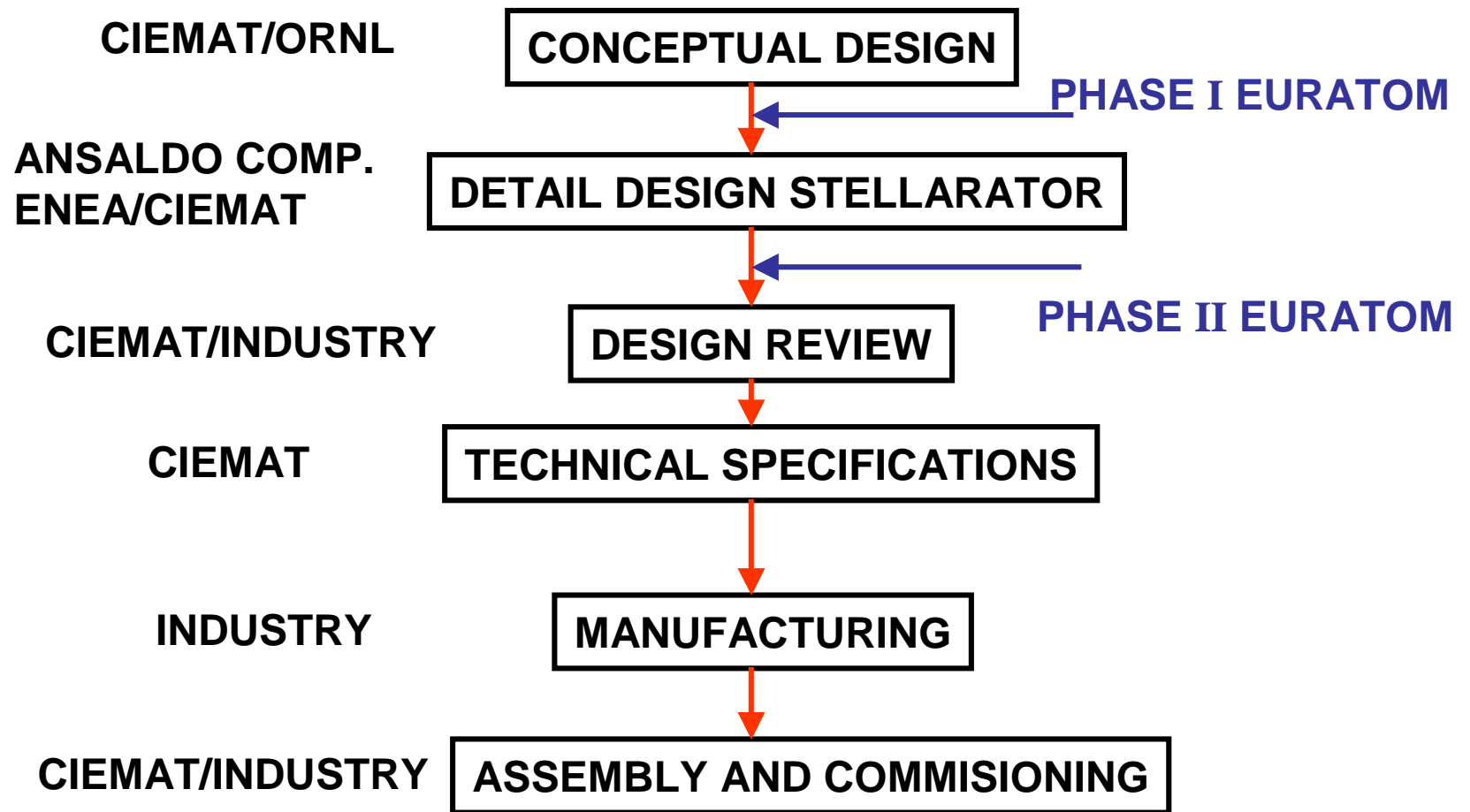
# Description of the device

## Support Structure (SS) & Poloidal Field coils (PF):

- 304 LN ( $\mu_{rel} \leq 1.01$ ) Cast pieces
- 4 vertical columns with transversal beams
- 4 U-shape rings, two inner, two outer
- 8+8 columns between upper/lower rings
- 4+4 radial beams between inner/outer rings
- 4 sets of PF coils inside rings



# Project development



## Project development

<b>Conceptual design start</b>	<b>1985</b>
<b>Phase I EURATOM approval</b>	<b>February 1986</b>
<b>Detail design start</b>	<b>October 1988</b>
<b>Phase II EURATOM approval</b>	<b>November 1989</b>
<b>Detail design end</b>	<b>June 1990</b>
<b>Design review end</b>	<b>January 1991</b>
<b>Component manufacturing</b>	<b>1991-1995</b>
<b>Assembly phase</b>	<b>1995-1996</b>
<b>Magnetic surface measurement</b>	<b>December 1996</b>
<b>Final tests and diagnostic assembly</b>	<b>1996-1997</b>
<b>First plasma</b>	<b>December 1997</b>

# Project development

## Basic components cost break-down:

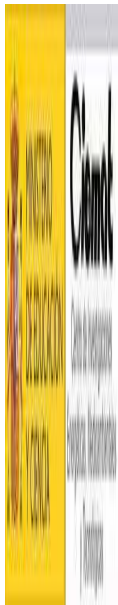
Component	Cost (MEuro)
Detail design	1.5
Central coils	1.2
Toroidal Field coils	1.02
Vacuum Vessel	3.9
Poloidal Field coils	0.31
Support Structure	0.55
<b>Total (on budget)</b>	<b>7.48 MEuro</b>

# Project development

## Systems cost beak-down:

System	Cost (MEuro)
Power supplies	10.5
Cooling system	0.58
Vacuum system	0.7
ECRH	2.9
NBI	~3
Control system	0.24
Experimental platform	0.06

**Total (on budget) 18.04 MEuro**



# Design and manufacturing

## Design strategy

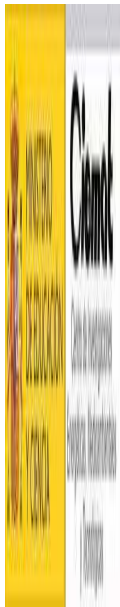
- Stellarators need a precise magnetic configuration, i.e., coils to be manufactured and assembled with tolerances within 0.1%
- High precision in the current supply to the coils
- Structures as rigid as possible, minimum deformation
- Maximum plasma volume, i.e., minimum distance between plasma and coils
- All the coils outside the Vacuum Vessel
- HC coils maximum reliability, the component can not be disassembled for repair
- Vacuum Vessel must allow access for NBI heating
- All auxiliary systems with industry except the Control System



# Design and manufacturing

## Quality Control

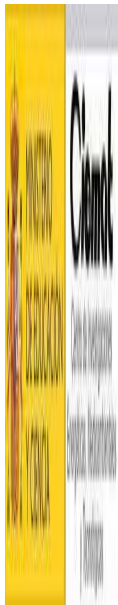
- VV and HC, the most critical components
  - After detail design a review by independent manufacturers
  - Verification of the F.E. calculations
- Verification of compatibility between components and between components and auxiliary systems
- Check dimensions and collisions with 1:1 scale mock-ups
- A detailed test program included in each manufacturing contract
- Cross check of the calculations done during detail design phase
- Close contract following-up during the manufacturing phase



# Design and manufacturing

## Central coils (HC). Reliability strategy

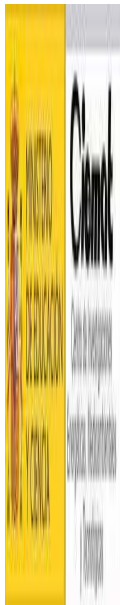
- No brazings between copper profiles within the coil body. Each layer (60 m) is a continuous length of conductor. (High current density  $\sim 100 \text{ A/mm}^2$ ). Each length/layer cooled independently
- Insulation system (fibre glass + epoxi resin) tested before manufacturing, demonstration of minimum requirements (shear strength at room temperature and at  $60^\circ\text{C}$ , static and fatigue tests). Independent tests at manufacturer and at CIEMAT
- Some specimens (to check insulation) impregnated with coils. Independent tests at manufacturer and at CIEMAT
- Dimensional control of the casing in a CNC machine, additionally by means of computerized theodolites. Checks for  $\mu_{\text{rel}} \leq 1.01$
- Current tests at maximum design parameters



## Design and manufacturing

### Toroidal Field coils (TF). Reliability strategy

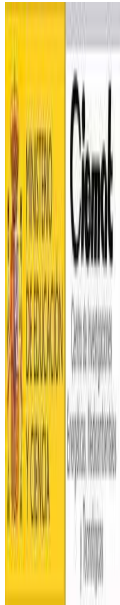
- Turns manufactured from copper plates by CNC machine
- Insulation system, similar strategy to HC
- Some insulation specimens impregnated with coils, similar strategy to HC
- Dimensional control of the structures: mechanical gauges, surfaces to be attached to the SS verified in a CNC machine. Checks for  $\mu_{rel} \leq 1.01$ .
- Current tests at maximum design parameters
- Manufacturing of two coil joint models (CIEMAT and manufacturer)
- Manufacturing of a full coil prototype



## Design and manufacturing

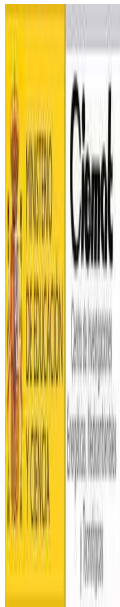
### Toroidal Field coils (TF). Reliability strategy

- A machine was built to test mechanically the momentums in coils during operation (CIEMAT)
  - Coil + support structure is located in position
  - The calculated electromagnetic forces the are integrated and concentrated in six points in the circumference of the TF structure
  - Six hydraulic cylinders apply the force at the same time. The cylinders are in one side or in the other side of the coil depending on the momentum to apply
  - Prototype coil was tested for 100000 pulses
  - Displacements were measured and compared with the calculations



## Design and manufacturing



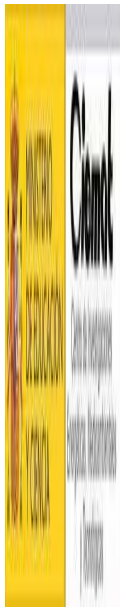


## Design and manufacturing

### Vacuum Vessel (VV). Reliability strategy

- High tolerances required because the coils and plasma proximity
- Detailed measurement of the permeability for the whole income material, weldings, pieces after forming, etc. ( $\mu_{rel} \leq 1.01$ )
- Prototype, two sectors + two rings, to study manufacturing problems
- High thermal flux test of groove area (plasma nearly touching)
- Test of VV prototype. Heated up to 150 °C (electrical heaters + eddy currents with the TF prototype coil). Vacuum seal test
- All the pieces measured in CNC machine and by means of theodolites
- Continuous measurement during assembly to minimize deformations due to the welding of the closing rings





## Design and manufacturing

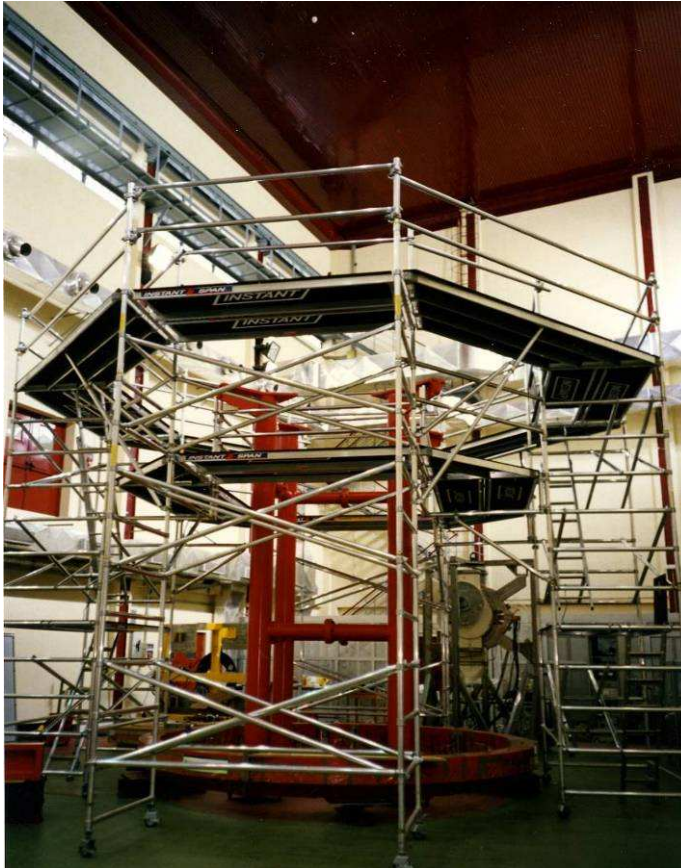
### Poloidal Field coils (PF). Reliability strategy

- High tolerances required because of the high requirements in the magnetic fields
- Insulation system, similar strategy to HC
- Some specimens impregnated with coils, similar strategy to HC

### Support Structure (SS). Reliability strategy

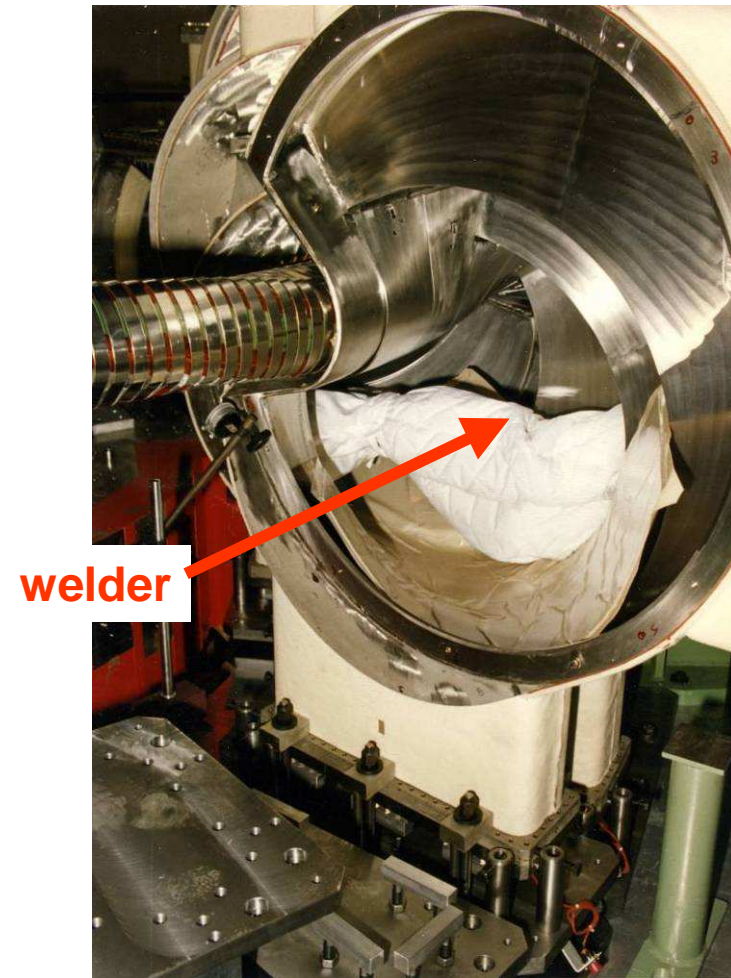
- High tolerances required (the components are assembled on it)
- Detailed measurement of the permeability for the whole income material ( $\mu_{rel} \leq 1.01$ )
- Dimensional control with theodolites at the factory and just after the assembly at CIEMAT

# Assembly and commissioning

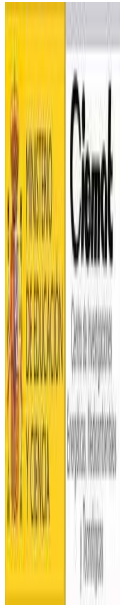




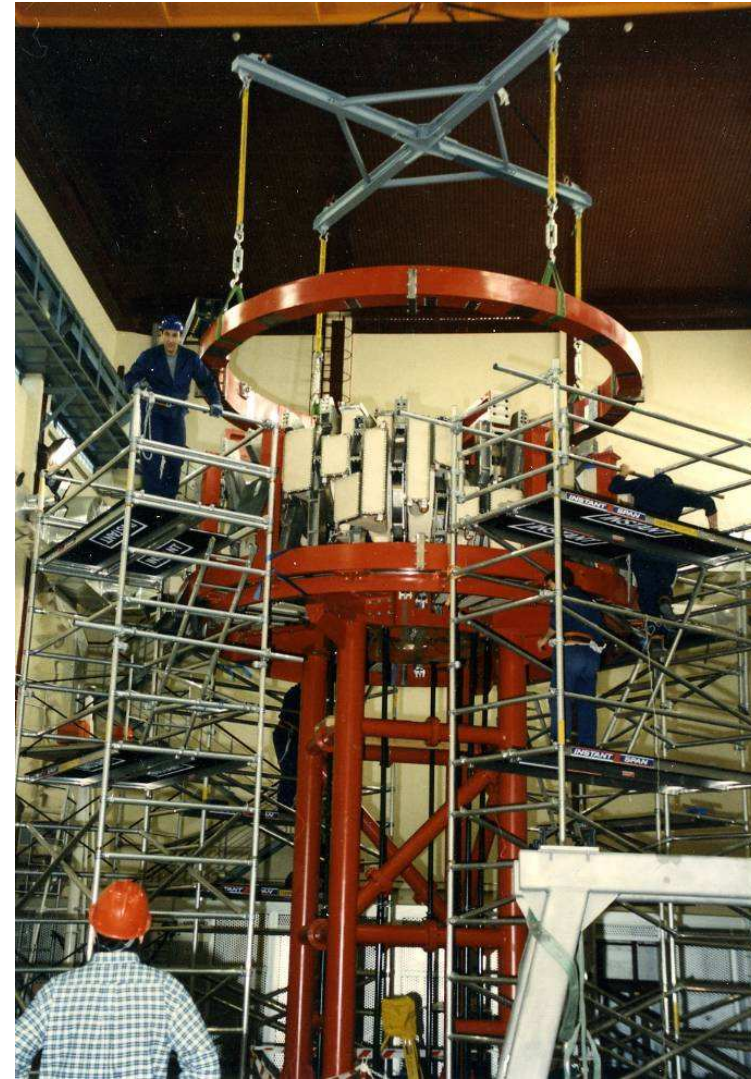
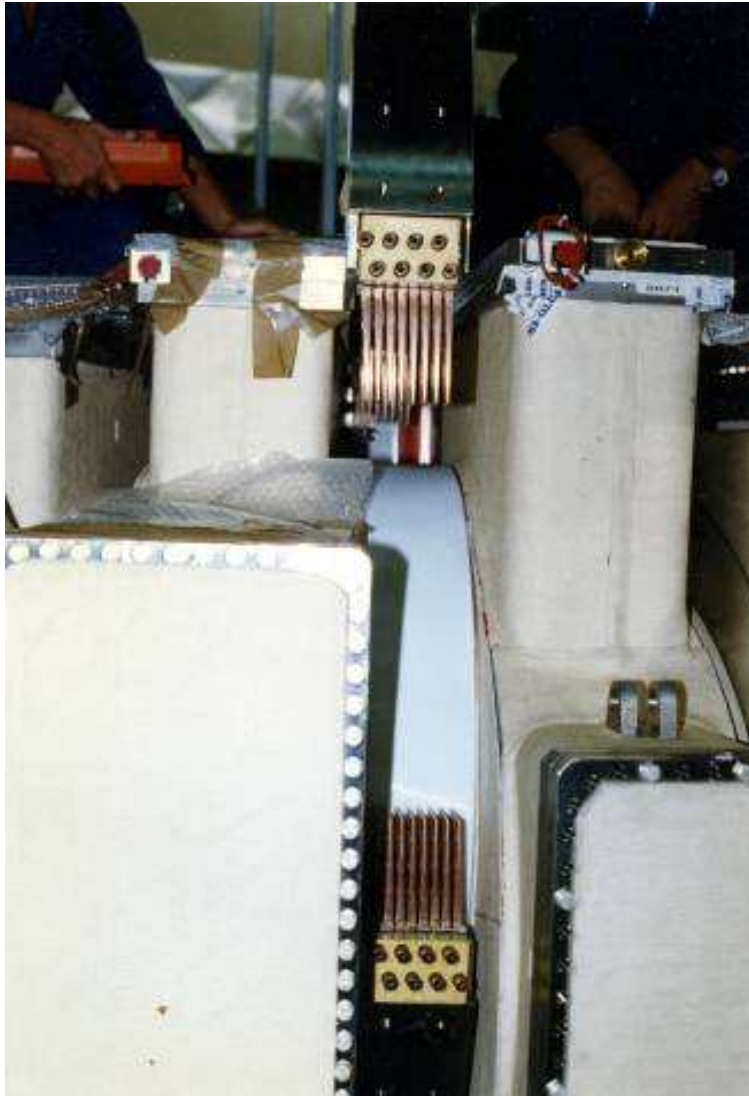
# Assembly and commissioning





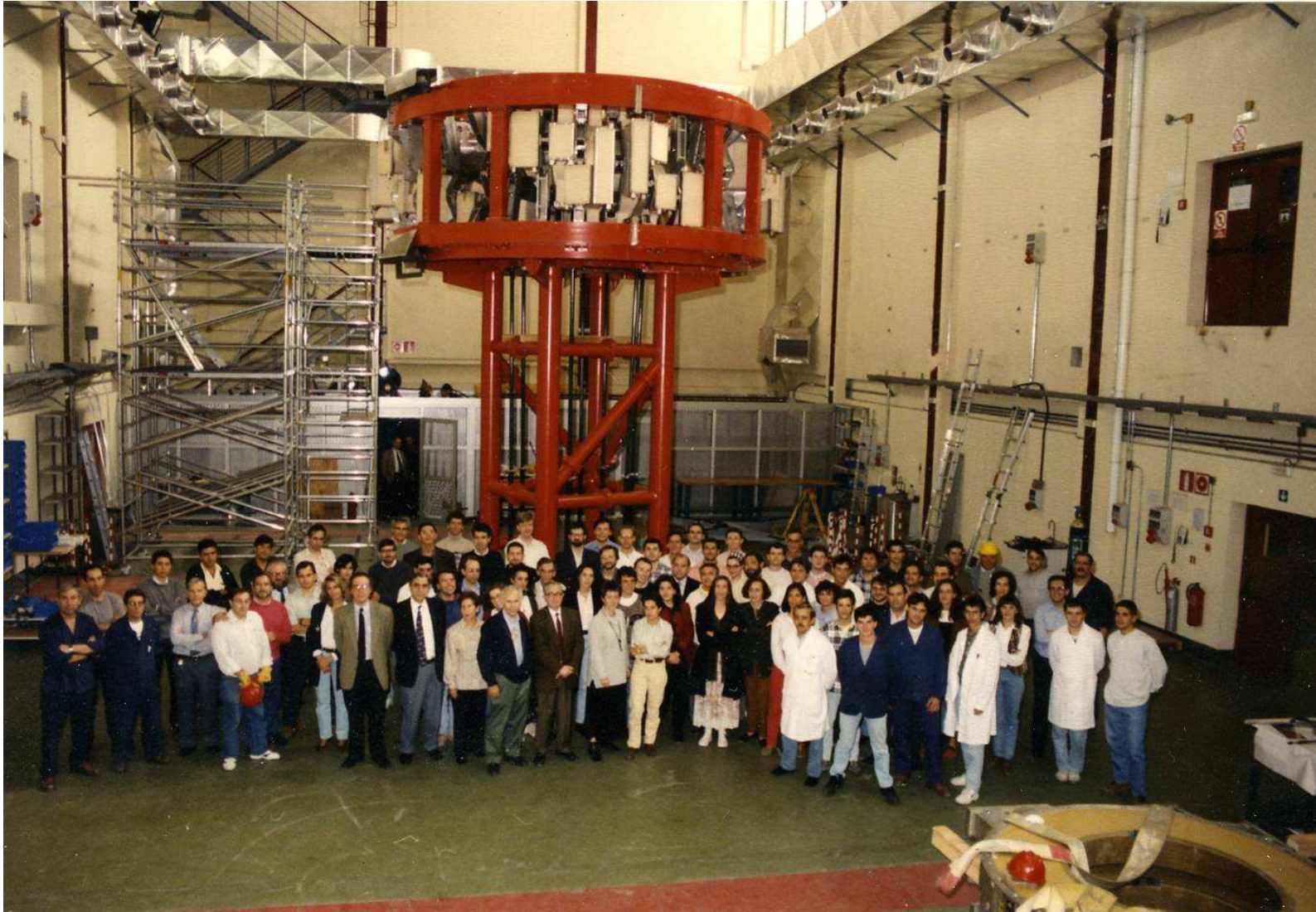


## Assembly and commissioning



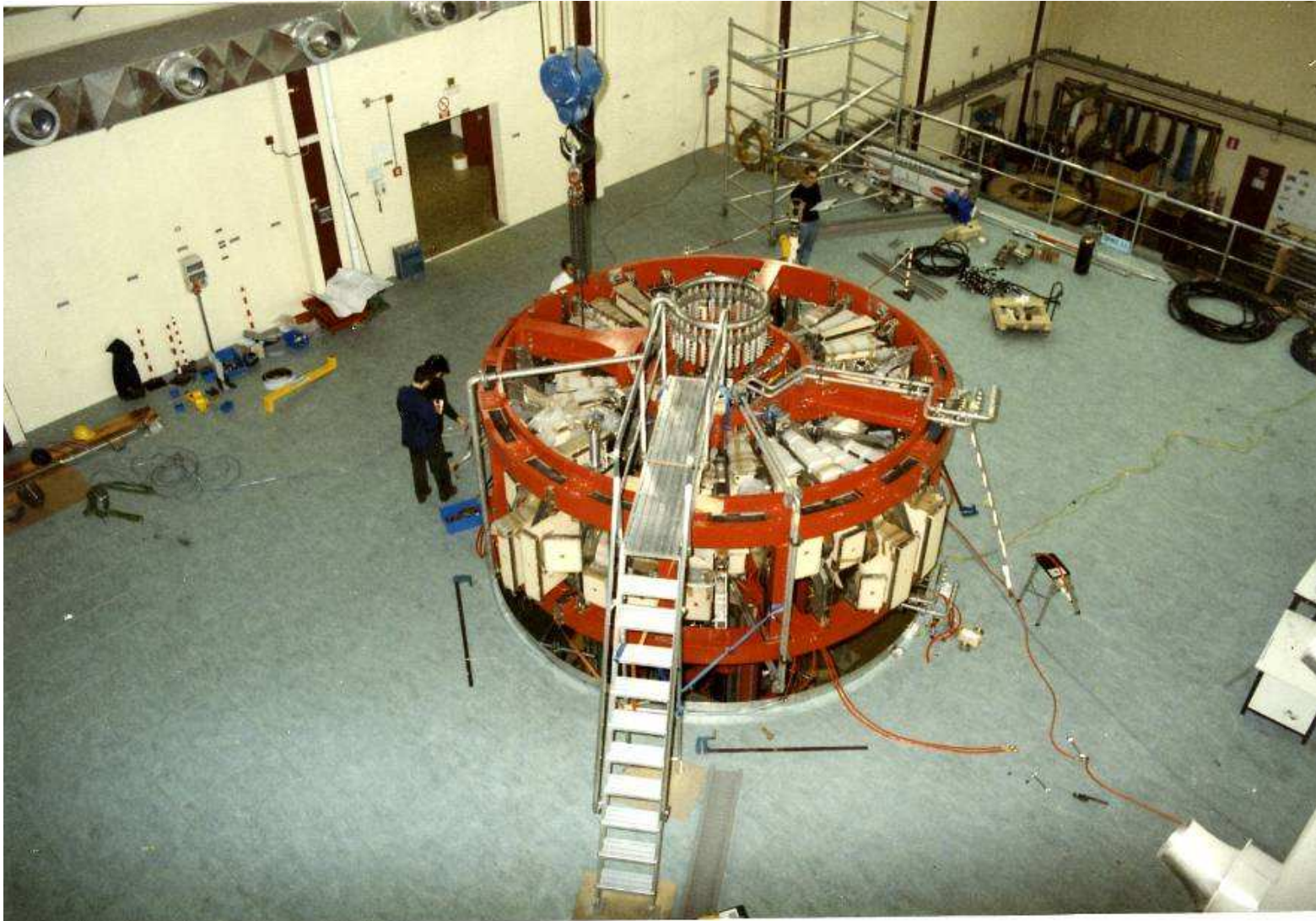


## Assembly and commissioning

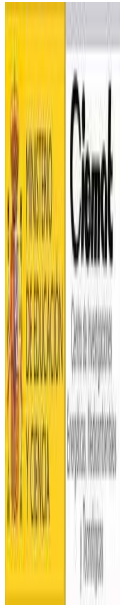




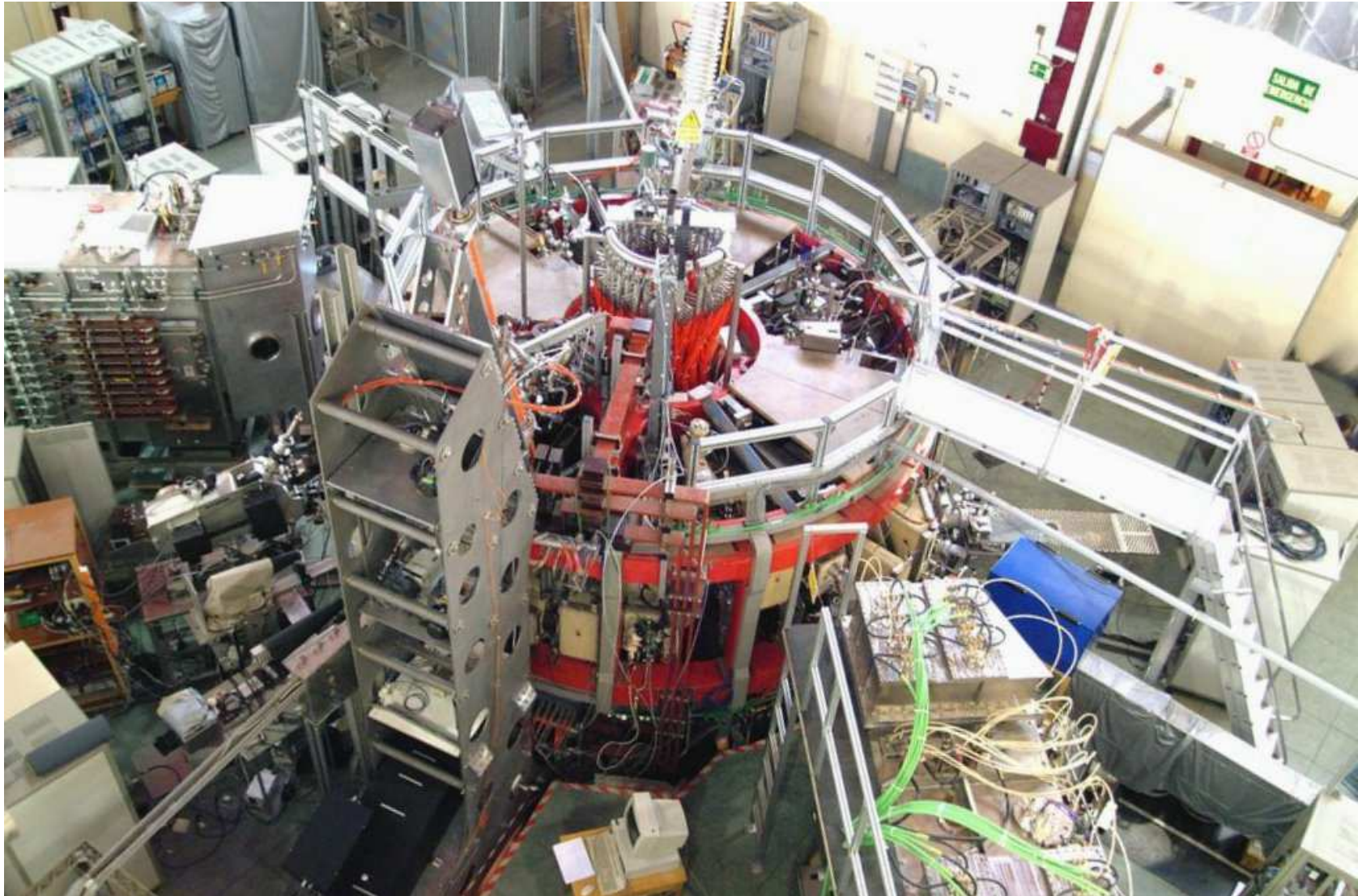
## Assembly and commissioning

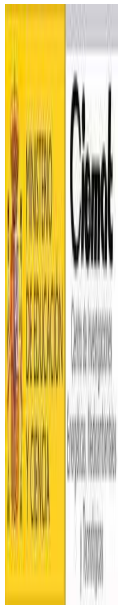






## Assembly and commissioning





## Assembly and commissioning

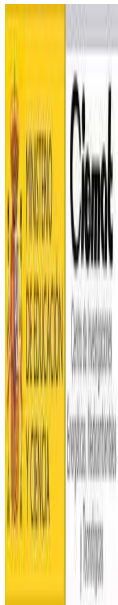
### Quality control during the whole assembly:

- Final position of the coils is a key point. Development of a dimensional control system (theodolites) (CIEMAT)
- Position of the components verified during assembly with reference marks made in the components during manufacturing, and targets in the torus hall walls
- TF coils verified electrically (insulation strength, resistance measurement, resonance capacitor discharge) just after assembly  
**(Two coils where removed and assembled again)**
- Distances HC and TF to VV less than 10 mm, measured with special gauges

# Assembly and commissioning

## Quality control during commissioning:

- Hydraulic tests in all circuits, coils included, after cooling system installation
- Leak test in VV after vacuum system installation
- Heaviest commissioning: power supplies. All rectifiers tested in dummy loads before energize the coils
- Coil full current tests after power supplies commissioning
- Test of the Control System and signal transmission with periphery control subsystems
- Magnetic surface measurements at 10% of the design field



## Operation comments

### TJ-II is not a nuclear installation but there are risks:

- High current in the coils and high magnetic fields
- High voltage in plasma heating systems and diagnostics
- ECRH quasi-optical transmission lines (based on mirrors)
- X-rays in the surrounding of the machine during current rump-up and rump-down in the coils
- High power lasers
- Fire risk (hydrogen, pressurized gases, ECRH, etc.)



## Operation comments

### Action to minimize risks:

- Ciemat has written procedures for the controlled access to the torus hall:
  - When normal plasma experiments
  - When tests on ECRH or high voltage systems
  - When Ti gettering pumps manipulation
  - When tasks inside the VV
- X-ray measurement campaigns
- Fire protection in all the areas with an early fire detection system dedicated for HV power supplies in the torus hall
- Laser paths enclosure
- High voltage systems shielded if possible



## Operation comments

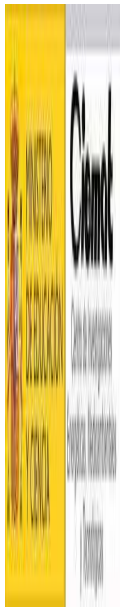
### Action to minimize risks:

- A dedicated system to control the ground loops in the torus hall developed by the TJ-II Control Engineering Group
- Periodic verification of TF electrical joints
- Contracts with industry for regular maintenance in:
  - The power supply system (every year)
  - The cooling system (every year)
  - The cranes (every year)
- Electrical risk evaluation and verification of the whole experiment (TJ-II, power supplies, diagnostics, etc.) every two years.

## Industrial relationships

### Conclusions according to the experience on all the phases of the TJ-II life:

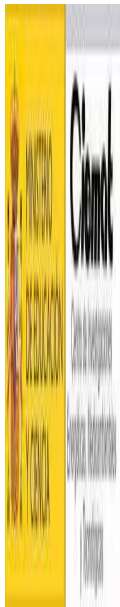
- Only a few companies were ready to assume some risks
- A few times the companies make the offers without a close study of the problem/component. Sometimes some hidden problems arise during design or manufacturing
- Offers were scattered, specially for PF coils. We had got 5 offers. Assuming  $C$  is the manufacturing cost, the other four offers were  $C+\delta C$ ,  $2xC$ ,  $2xC+\delta C$ ,  $5xC$ !
- Sometimes manufacturing procedures are not well studied to reach tolerances.



## Industrial relationships

### Conclusions according to the experience on all the phases of the TJ-II life:

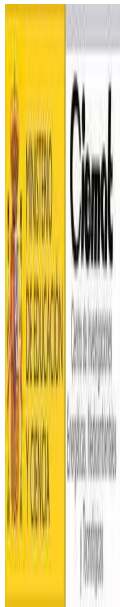
- To fulfil with some special requirements ( $\mu$ rel) some material in some components was refused
- Good quality of the final components although all the contracts with discussions for extra money (sometimes for CIEMAT faults, sometimes because industry underestimations)
- Control System built, commissioned and operated by TJ-II Control Engineering Group. Small contracts for specific subsystems not good result. Difficult for outside people to understand the problems, and very expensive. Necessary modifications fast and cheap.



## Industrial relationships

### Conclusions according to the experience on all the phases of the TJ-II life:

- Assembly by CIEMAT (VV by De Pretto Escher Wyss). External companies very expensive prices
- Sometimes difficult for maintenance companies to understand that if we loose time we are loosing money ("we do only experiments")
- Inspection of the electrical installations is highly necessary to avoid the tendency to the chaos of the "experiment". The company is changed from time to time to avoid "excessive knowledge" of the systems
- Failure of components (RAM analyses) now under study by Engineering School of UPC (Barcelona)



# Industrial relationships

**END**